Incorporating Knowledge Base Techniques in Radar Signal Processing

Past, Present & Future

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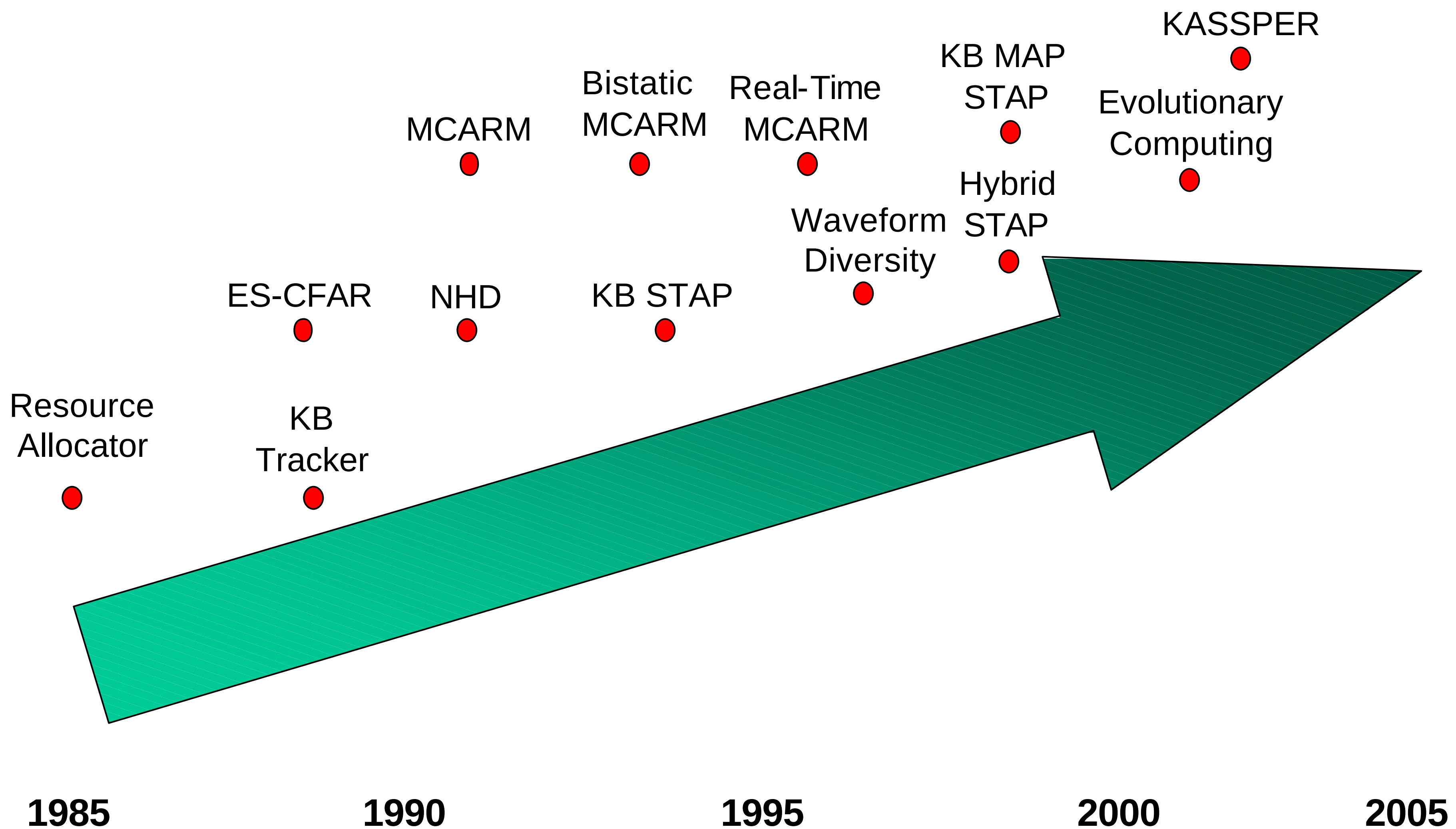
AFRL Sensors Directorate

History

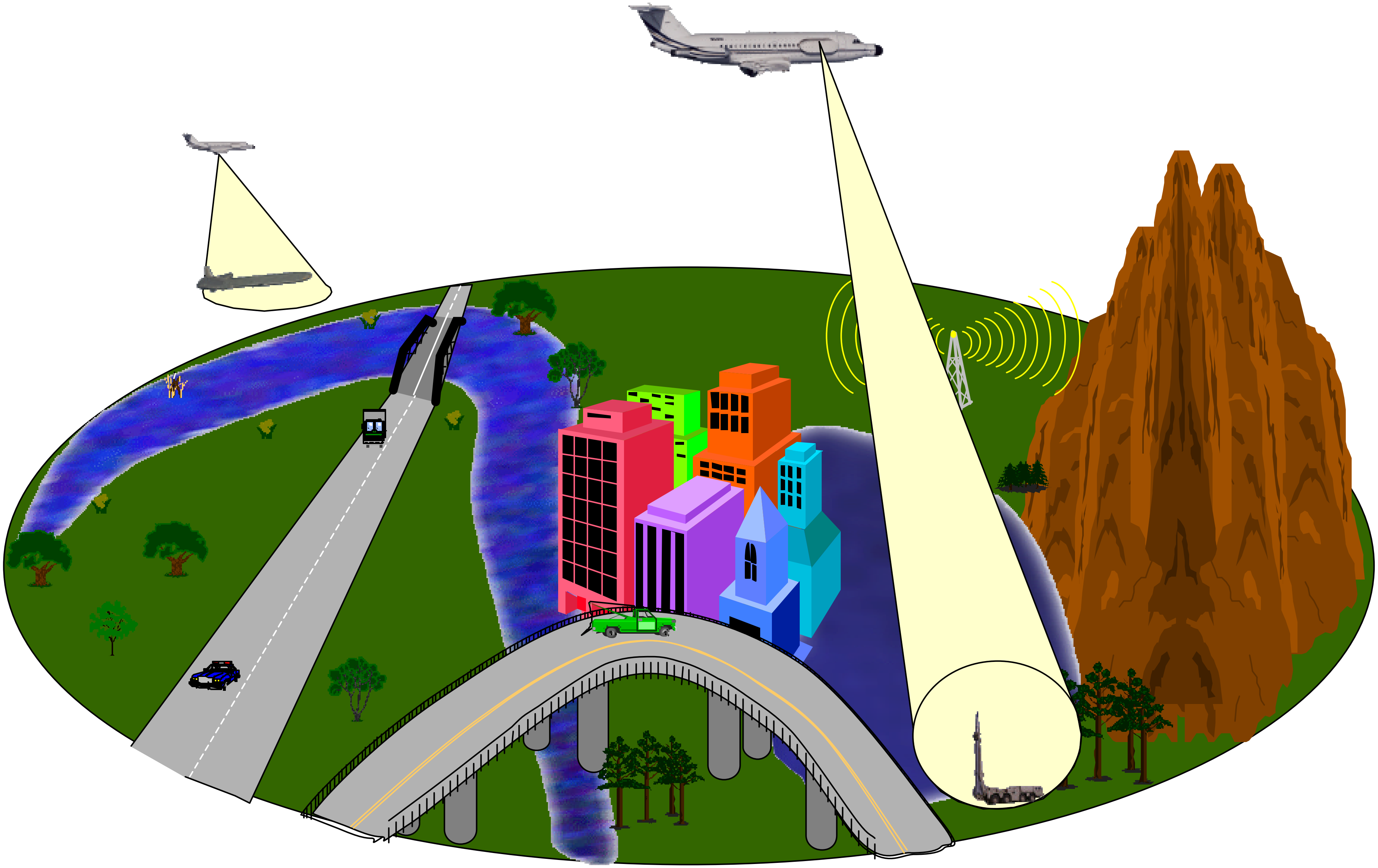

KASSPER
KB MAP STAP
Evolutionary Computing
Bistatic MCARM
Real-Time MCARM
MCARM
Hybrid STAP
Waveform Diversity
ES-CFAR
NHD
KB STAP
Resource Allocator
KB Tracker
1985
1990
1995
2000
2005

Selected AI Research Topics at Rome

- **Surveillance Internetting/ID, 1982.** ***Aim:*** **"Autonomous Control of Distributed Tactical Sensor Networks."** ***Source:*** **Rome Research Site Archives.**
- **Advanced Onboard Signal Processor (AOSP), 1982. Nine-node Experimental AOSP Developed.** ***Aim:*** **Multi Mission Signal Processing for Sensors in Space, Including Fault Detection & Reconfiguration Actions.** ***Source:*** **Rome Research Site Archives.**
- **Adaptive Control of Multi-Domain Sensor Processor, 1986.** ***Aim:*** **Apply AI for Controlling Parameters & Modes of Advanced Multi-Function Radar Systems.** ***Source:*** **Rome Research Site Archives.**
- **Expert System CFAR, 1988.** ***Aim:*** **Apply AI to Select & Apply CFAR Detector in Radar.** ***Source:*** **Rome Research Site Archives.**
- **Tactical Expert Mission Planner (TEMPLAR), 1989.** ***Aim:*** **Apply AI to Preparation of the Air Tasking Order (ATO).** ***Source:*** **Rome Research Site Archives.**
- **ELINT Expert Tutor, 1990.** ***Aim:*** **Apply AI to the Training of Signal Intelligence (SIGINT) Analysts at the Foreign Technology Division (FTD).** ***Source:*** **Rome Research Site Archives.**
- **AI Algorithms for Sensor Fusion, 1994.** ***Aim:*** **Apply AI to Automatic Target Recognition.** ***Source:*** **Rome Research Site Archives.**
- **Knowledge Base STAP, 1995.** ***Aim:*** **Apply AI to Assess the Environment & Apply the Most Appropriate STAP Algorithm.** ***Source:*** **Rome Research Site Archives.**

Motivation for Knowledge Aided Approaches to Radar Signal and Data Processing

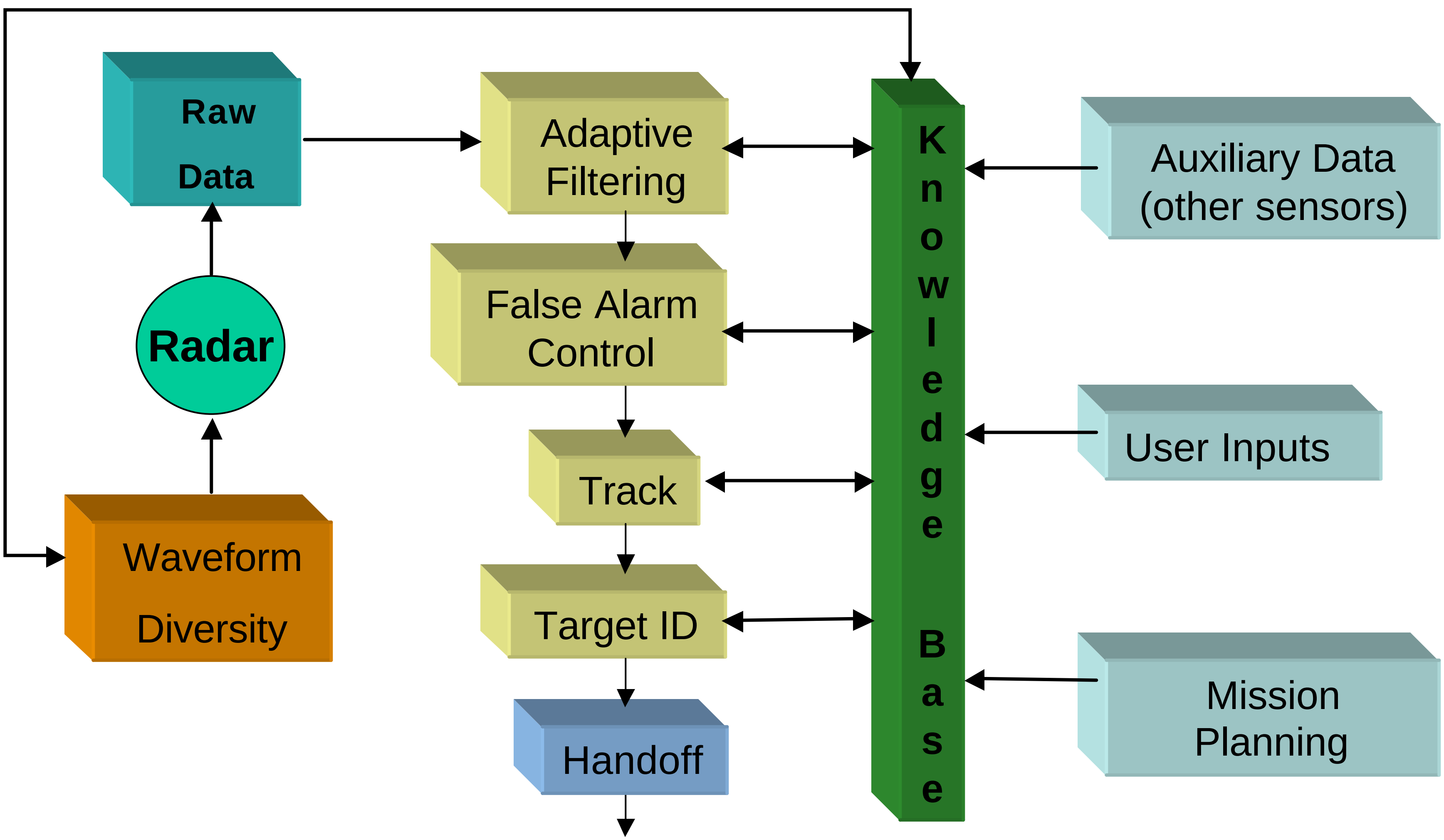
Dynamic & Non-Homogeneous Background Environment



The Benefit

- **Greater than 10 dB End-to-End Radar Performance Improvements in Real-World Dynamic & Non-Homogeneous Environments**
  - **Airborne Radar**
  - **Space-Based Radar**
- **Enhanced Subclutter Visibility**
  - **AMTI**
- **Lower Minimum Detectable Velocity (< 0.1 Knot)**
  - **GMTI**
- **Improved Discrimination and/or Identification**

Integrated End-to-End Radar Signal & Data Processing



Integrated Knowledge-Based Signal & Data Processing

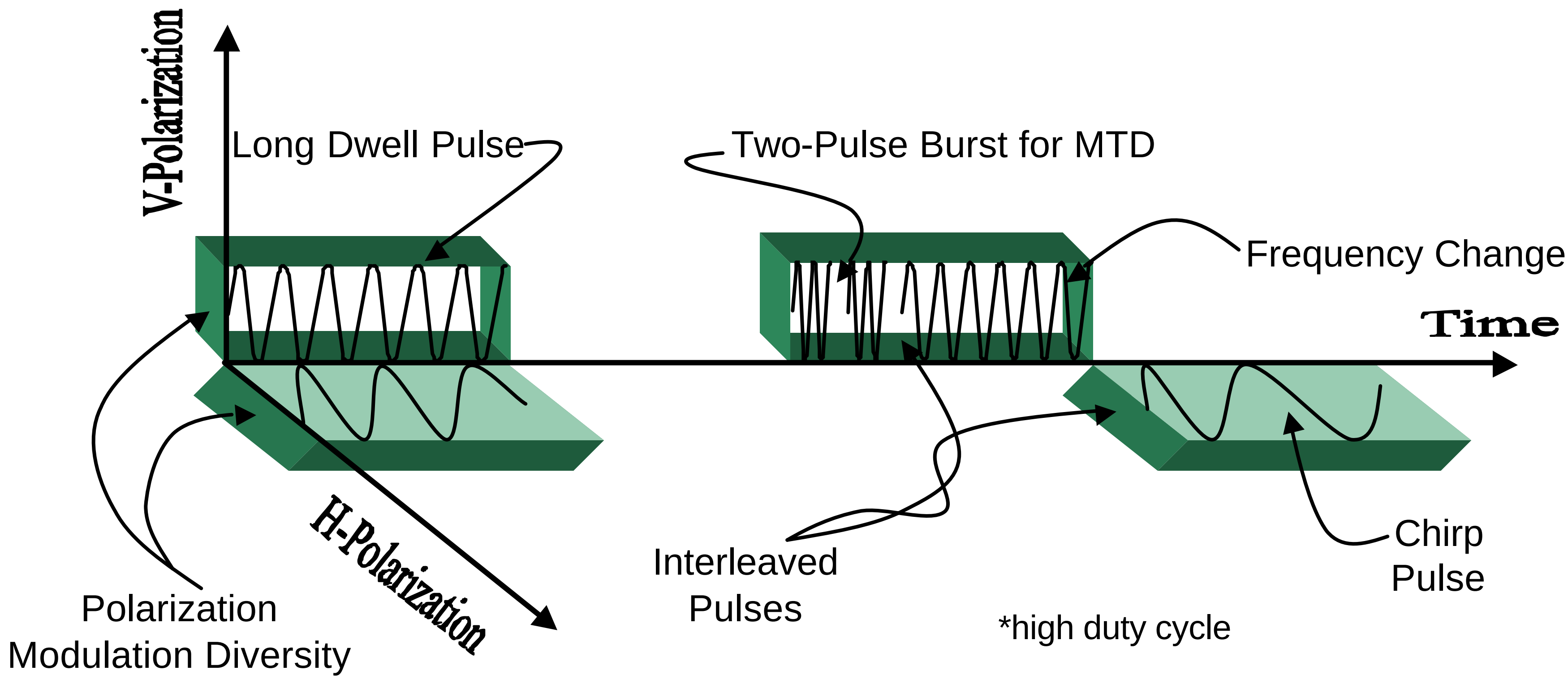
- **Each Stage of Processing Affects the Others**
- **Best Overall Performance is Achieved From an Integrated End-to-End Approach**
  - **Requires Integrated Design**
  - **Not Merely Data Passing From One Stage to the Next**
    - **i.e. Match Degrees of Freedom, Statistics & Detector Design**
  - **Adaptivity & Feedback/Forward Essential**
  - **Waveforms Matched to the Problem**

Waveform Diversity & Knowledge Base Control

Transmit Waveform Diversity

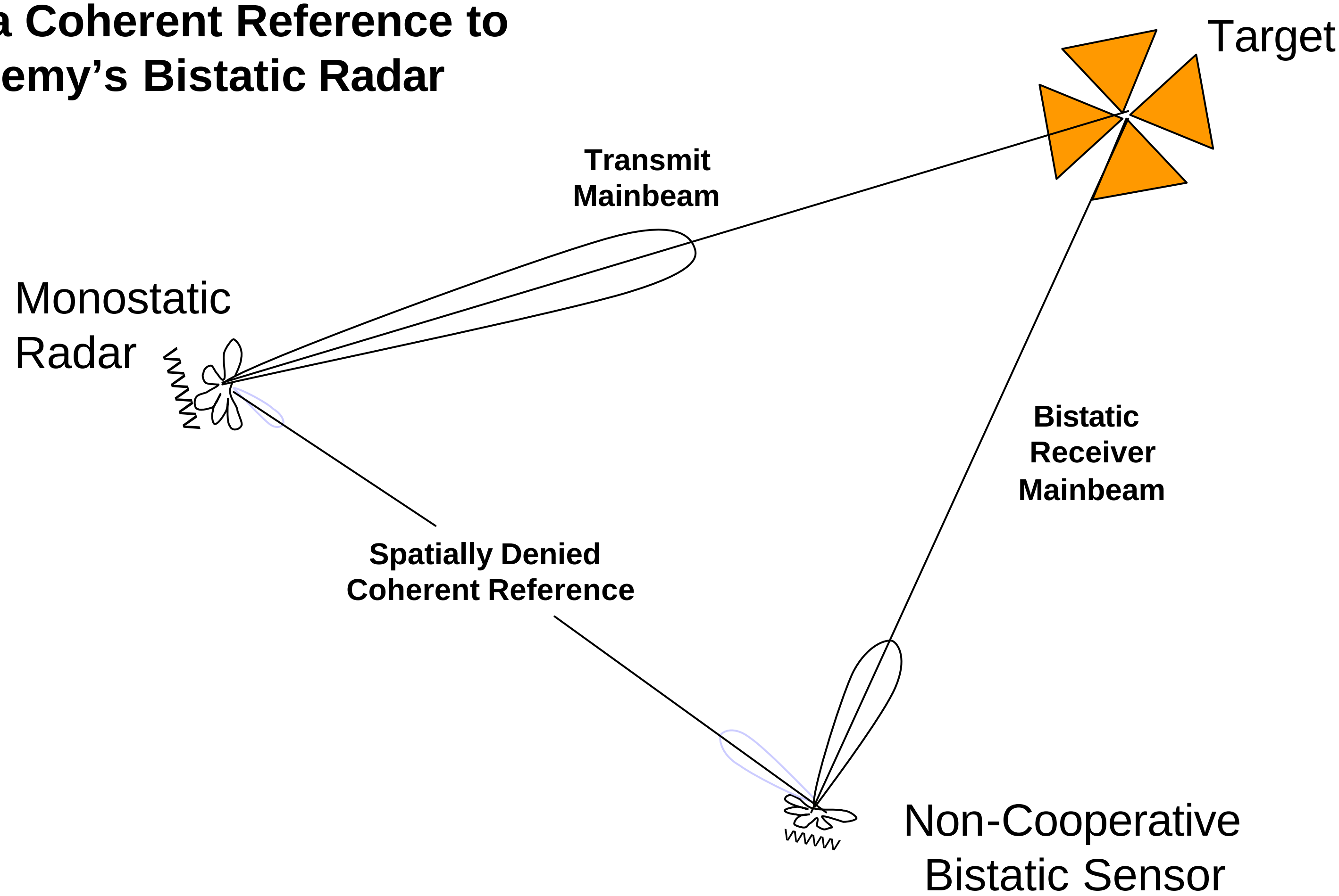
Some Applications

- **Optimal Selection of Waveforms Based on Environmental Assessment**
- **Spatial-Temporal Denial of Enemy Sensors and Systems**
- **Simultaneous, Multi-Mission Waveforms, e.g. GMTI, AMTI, Track, ATR (“systems approach”)**
- **Innovative Waveforms for New Missions (FOPEN, GPEN, etc.)**



Spatial Denial – One Reason for Waveform Diversity

Deny a Coherent Reference to the Enemy's Bistatic Radar



Expert System CFAR

Expert System CFAR

- **ES-CFAR Was Our First Attempt at Using AI to Select Radar Signal Processing Algorithms & Parameters**

- **The CFAR Problem**

  – **Fielded Radar Signal Processors Are Designed To Use A Single, Fixed CFAR Algorithm**

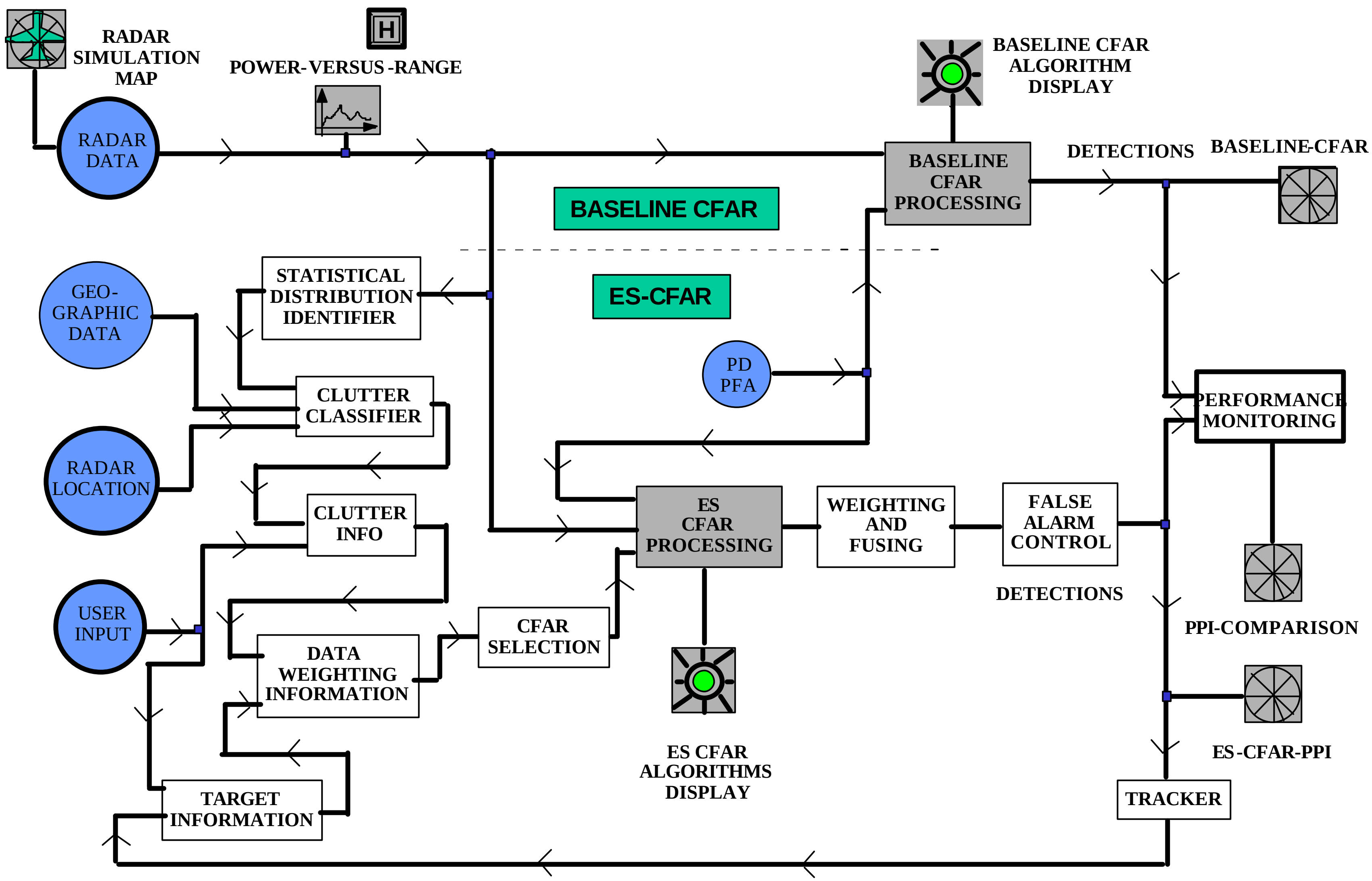
  – **Any Given CFAR Algorithm Is Designed With Assumptions About The Background & Will Perform Optimally When These Background Conditions Are Realized In The Environment**

  – **In a Typical Airborne Radar Environment Clutter Parameters Are Dynamically Changing & a Single, Fixed CFAR Processor Will Exhibit Excessive False Alarms & Detection Degradation in Regions Where The Background Characteristics Violate The Design Assumptions**

Our Approach

- **Detection Processor Capable Of:**
  - **Monitoring The Radar Clutter Environment**
  - **Determining The Statistical Characteristics**
  - **Matching The CFAR Algorithm To The Environment**
    - **Choice Of 4 Algorithms**
      - **CA, GO OS and TM CFAR**
    - **Variable Reference Window Size**
- **Payoff:**
  - **Improved Target Detection**
  - **Reduced False Alarms**
  - **Easily Implemented & At Relatively Low Cost**

ES-CFAR Prototype



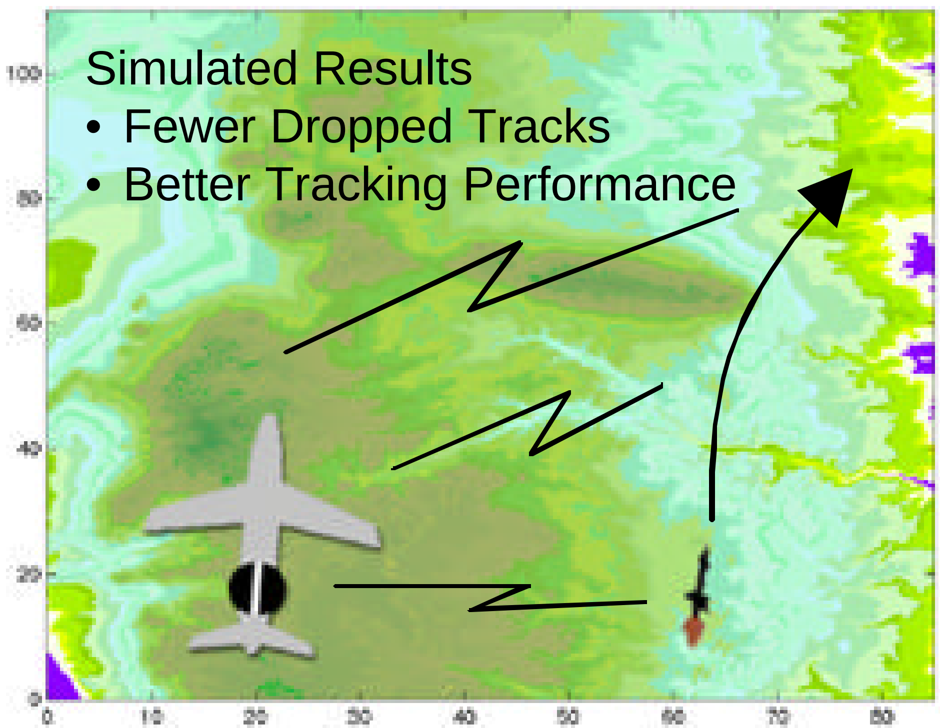
Measured Data Summary

	EXPERT SYSTEM CFAR		BASELINE CELL-AVG.		BASELINE ORDERED STAT.	
DESIRED P_{fa}	P_d	P_{fa}	P_d	P_{fa}	P_d	P_{fa}
1e-3	0.92	1.2e-3	0.62	2.5e-3	0.67	4.4e-3
1e-4	0.90	3.9e-4	0.51	8.0e-4	0.64	2.3e-3
1e-5	0.87	1.3e-4	0.44	3.3e-4	0.62	1.5e-3
1e-6	0.87	4.0e-5	0.28	1.6e-4	0.56	1.1e-3

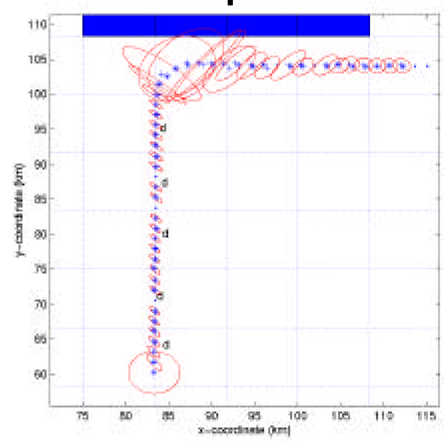
- THE INCREASE IN SINR OTHERWISE REQUIRED TO IMPROVE DETECTION PERFORMANCE BY THIS AMOUNT IS ~ 5dB

KB Tracker

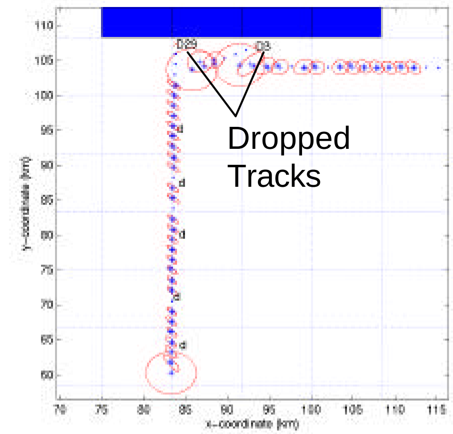
Knowledge-Based Tracking



With Maneuver Anticipation

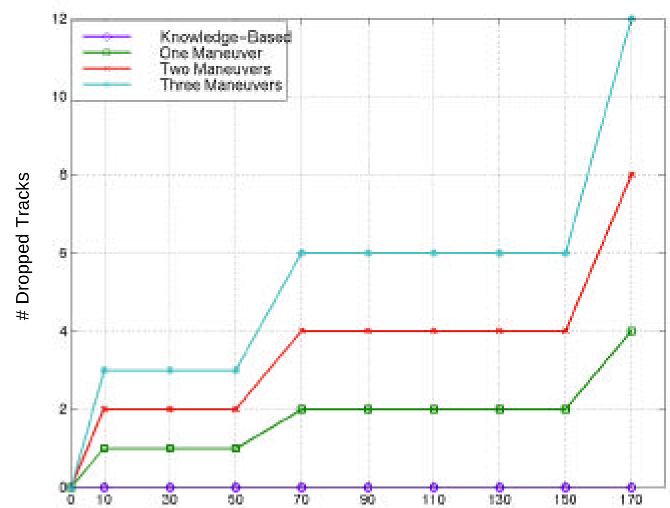


No Maneuver Anticipation



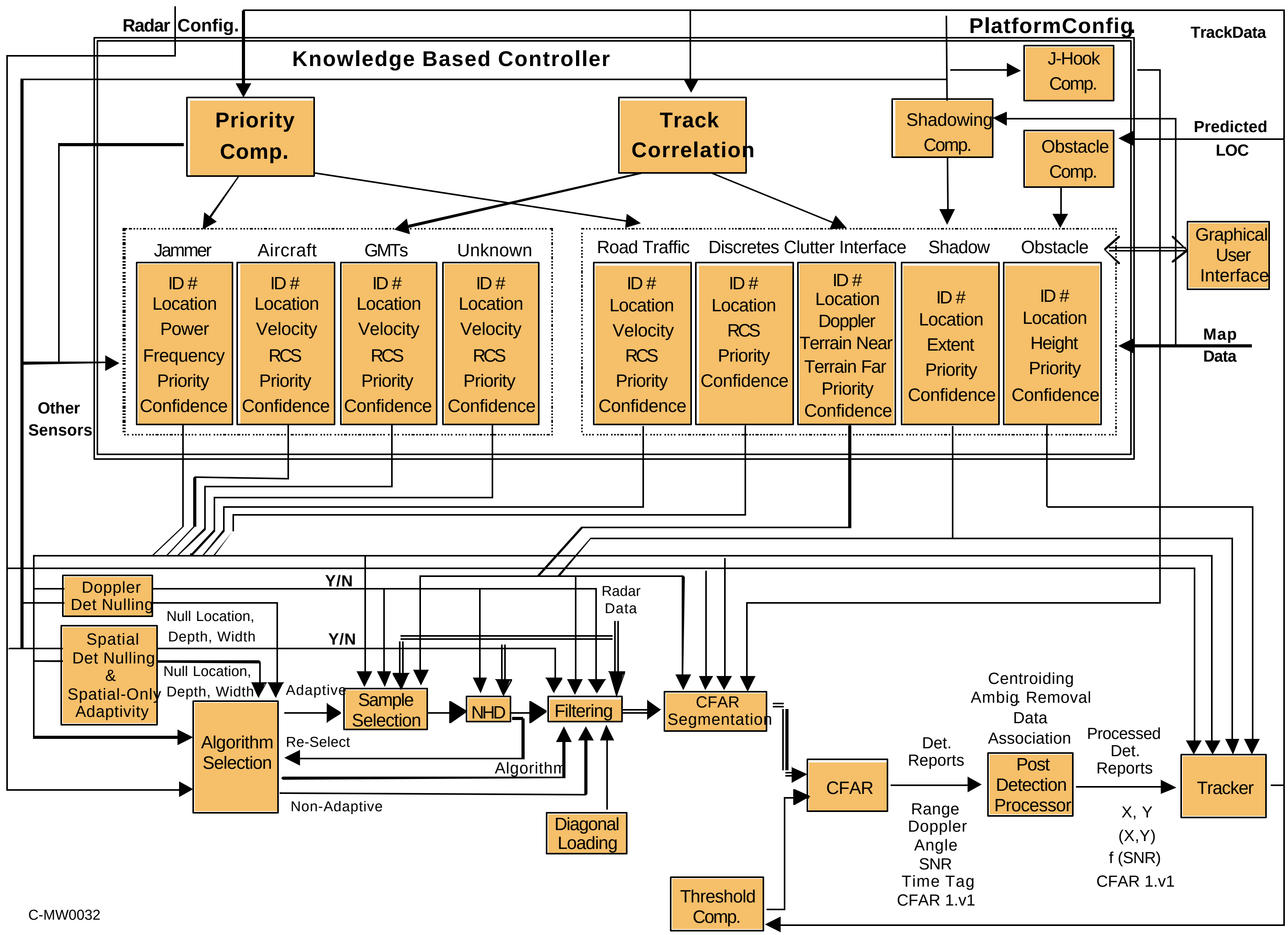
Knowledge-Based Anticipates:

- **Maneuvers**
- **Shadowing**
- **Discretes**
- **Road Traffic**
- **Multiple Targets**



KB STAP

Controller for KB STAP



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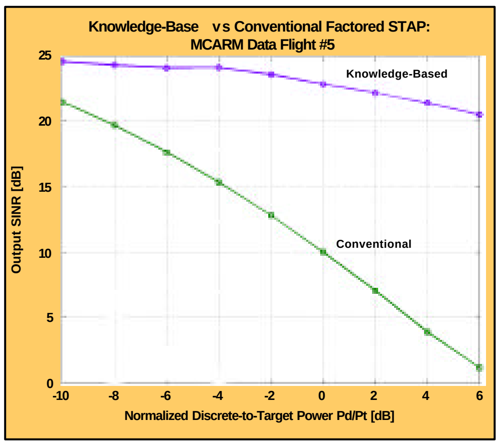
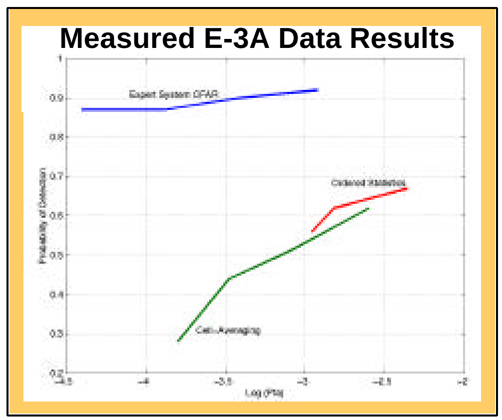
KB STAP

- **The Logical Extension of ES CFAR to the Filter Stage of Processing**
- **End-to-End Processing was Investigated Under KBSTAP**
  - **Lower MDV**
  - **Smaller RCS**

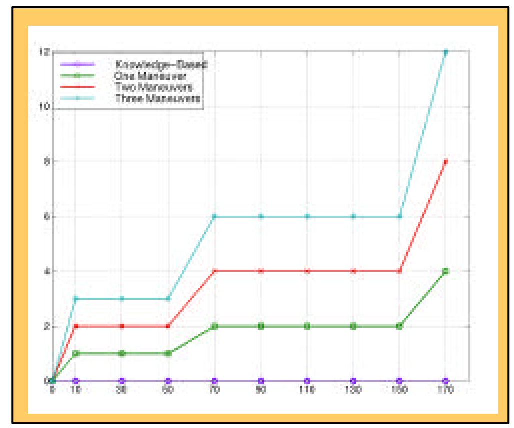
KB-STAP



ES-CFAR



Tracking

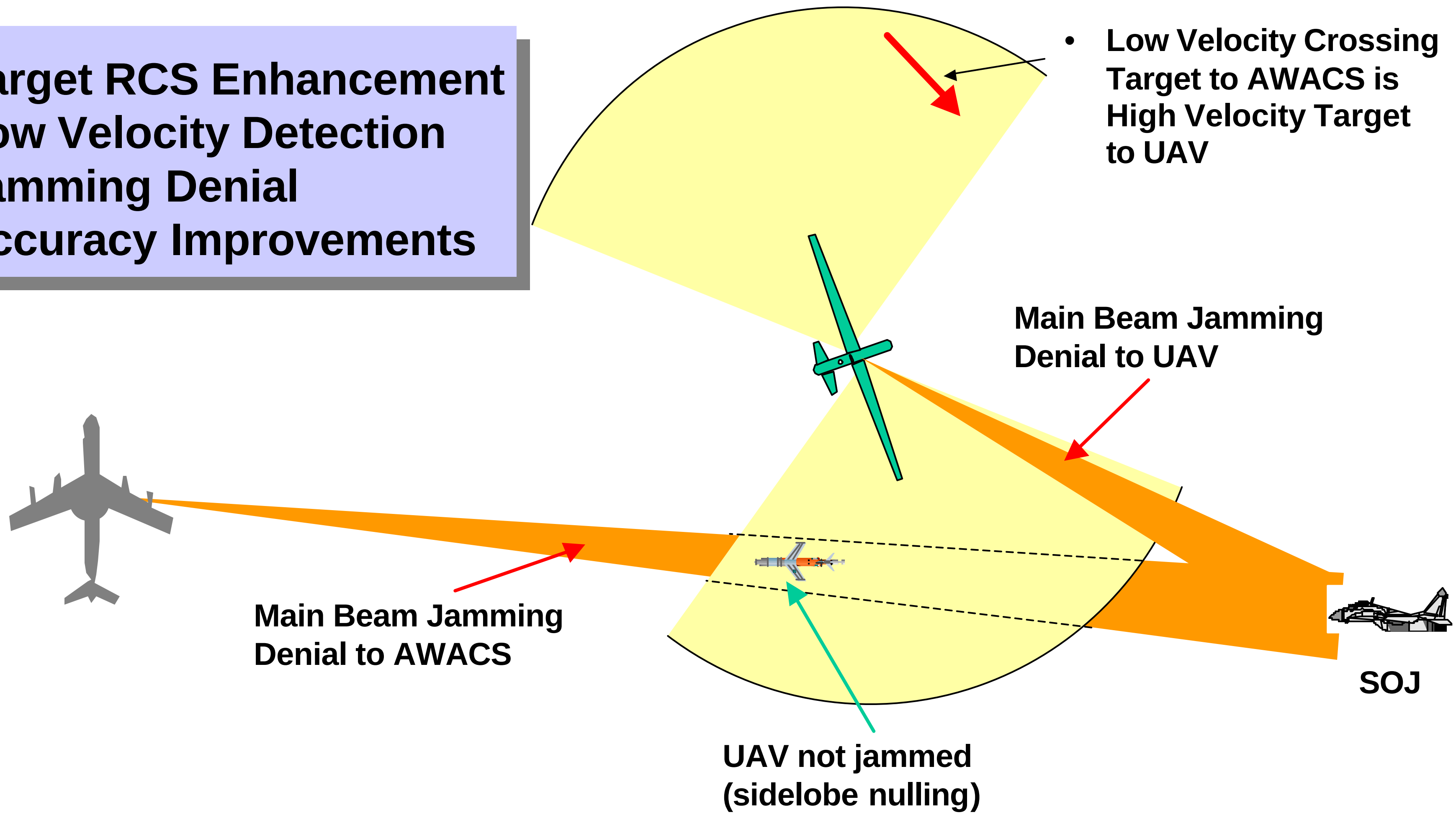


Raw Data → **Filtering** → **Detection** → **Track** → **To User**

Filtering	Detection	Track
+5dB	+5dB	+3dB

KB STAP in Bistatic/Multistatic Radar

- Target RCS Enhancement
- Low Velocity Detection
- Jamming Denial
- Accuracy Improvements



Bistatic Radar

- **Payoff**
  - **2 Orders of Magnitude Improvement in Noise**
  - **3 Orders of Magnitude Improvement in Clutter**

Range	**12dB**	
Losses	**2dB**	
RCS Enhancement	**10dB**	
	24dB	**In Noise**
Signal Processing	**10dB**	
	34dB	**In Clutter**

KB - Why Now?

- **Potential Performance Gains Demonstrated with Advanced Algorithms**
  - **KB-STAP**
  - **Expert System CFAR**
  - **Knowledge-Based Tracking**
- **Emerging Embedded Processing Technology Provides Capability to Implement in Real-Time, Fielded Systems**
- **Waveform General Timing & Control Now Permits Interleaved & For Simultaneous Waveforms**

Now We Can Demonstrate

Performance Gains of *Integrated*

Knowledge-Based Processing in *Real-Time*

Methodology

- **"… Substantial Performance Improvements Will Likely Not Be the Result of Higher Power-Aperture Products"**
- **"… Substantial Performance Gains Will More Likely Be the Result of Advanced Processing Techniques"**
- **Careful Selection of Algorithms, Parameters, and Training Data Produces Significant Performance Improvements Over Conventional Processing**
- **An** *Integrated* **Approach to Dynamic Waveform Selection & Signal Processing (Filtering, Detection, Tracking, Identification,…)**
- **Greatest Improvements are Achieved in the Most Severe Environments**

Intelligent Use of CFAR Algorithms, RL-TR-93-75, May 1993.

Novel Diverse Waveforms, AFRL-SN-RS-TR-2001-52, June 2001.

Knowledge-Base Applications to Ground Moving Target Detection, AFRL-SN-RS TR-2001-185, August 2001.

Measured Data is Important!

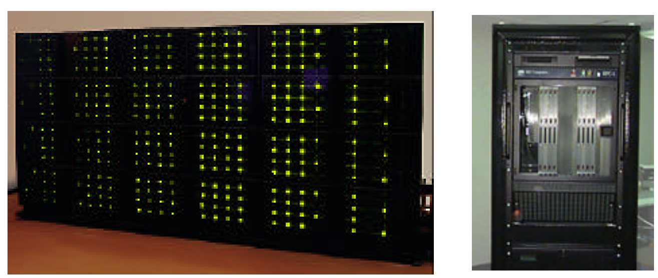
Sensors Surveillance Facility
Rome Research Site

Multi-Channel Airborne Radar Measurements

S-Band Dual Polarized Track and Imaging Radar

C-Band Multi-Channel Dual Polarized Phased Array Radar

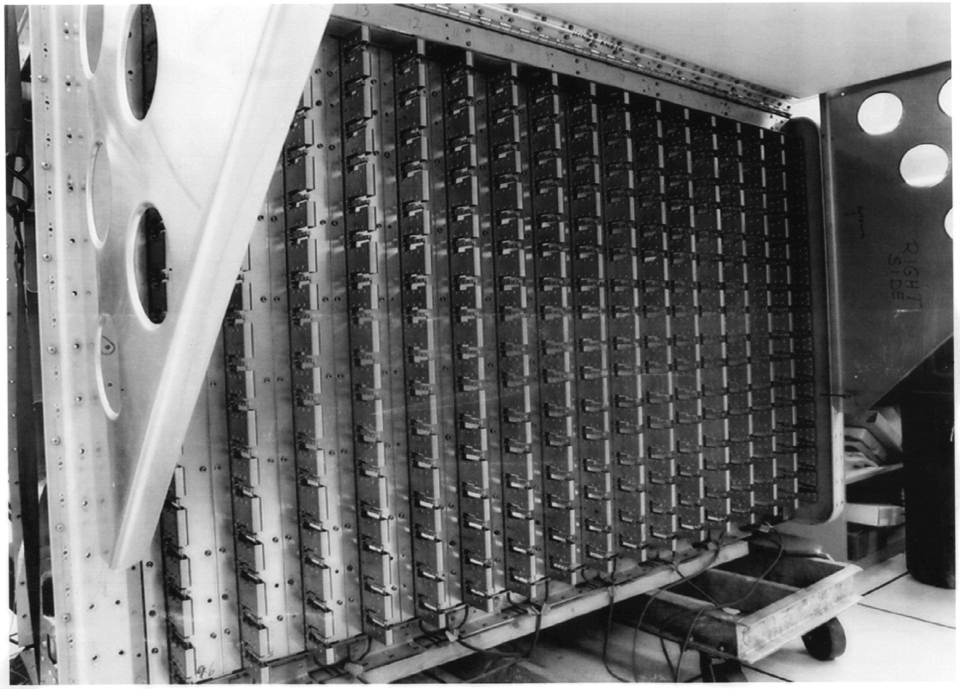
ESM/Bistatic Sensor Test Bed



High Performance Computing

L-Band Search Radar

MCARM Testbed & Antenna Array



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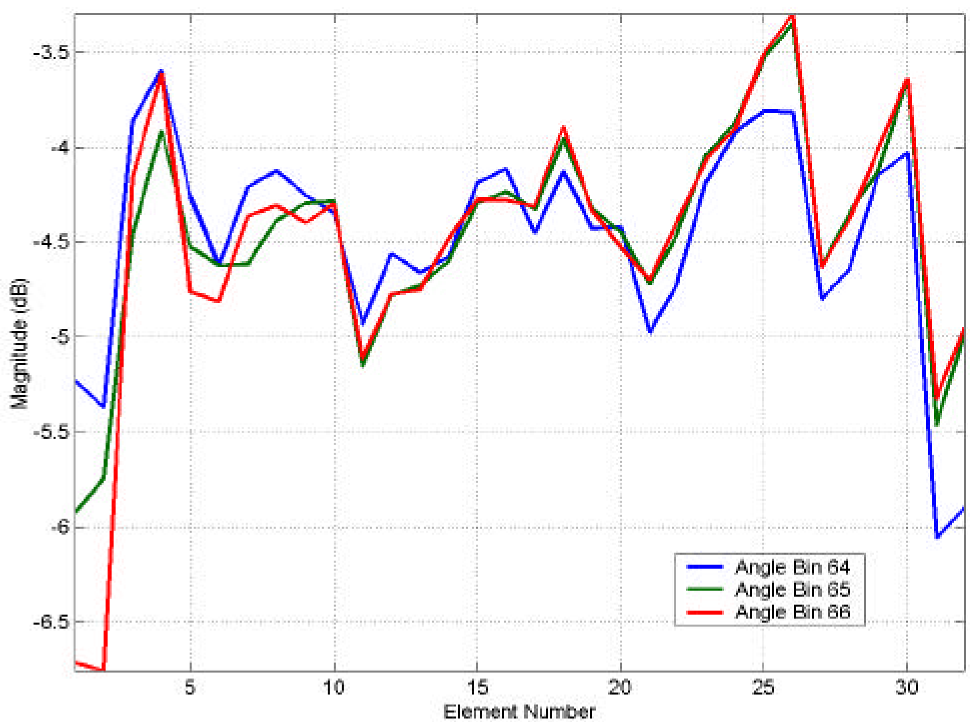
Magnitude of MCARM Steering Vectors

Ideal Array

$$s = \left[1 \;\; e^{jkd\sin(\theta)} \;\; e^{j2kd\sin(\theta)} \;\; \cdots \;\; e^{j(N-1)kd\sin(\theta)} \right]^T$$

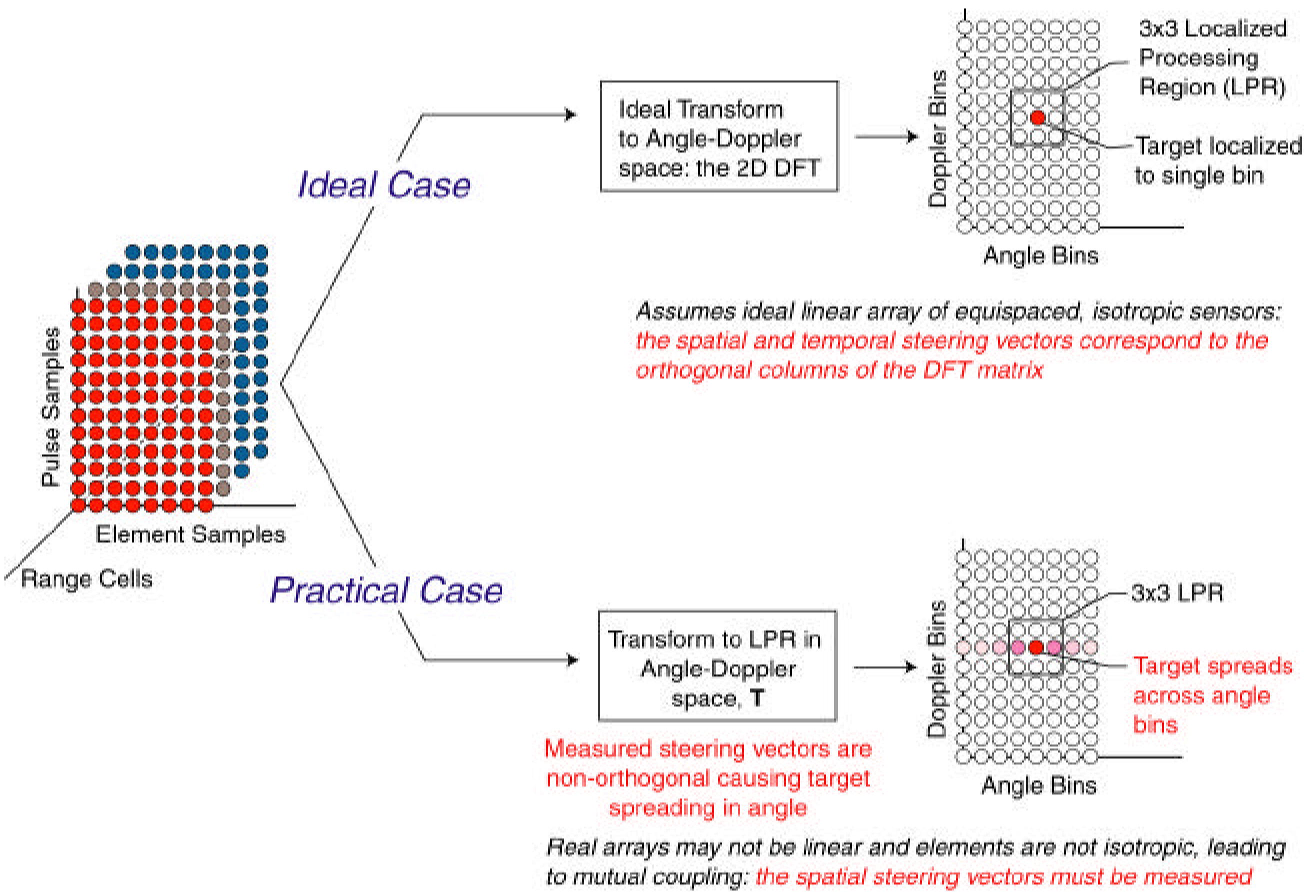
- Very Similar to Fourier Coefficients

MCARM Array



Practical STAP Processing

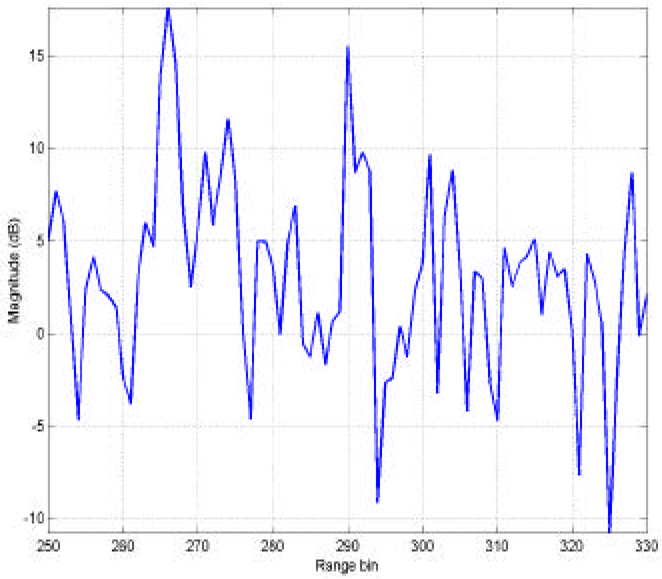
JDL Algorithm



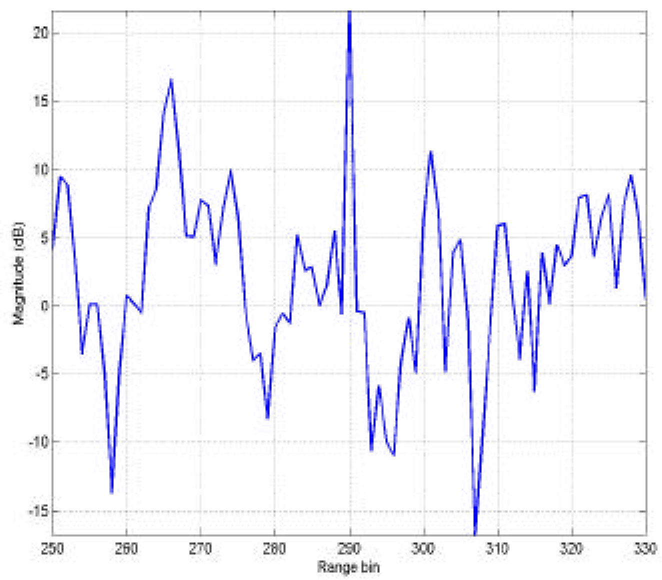
Accounting for real antenna effects significantly improves on traditional STAP processing

Measured Steering Vectors: JDL

Assuming Ideal Array



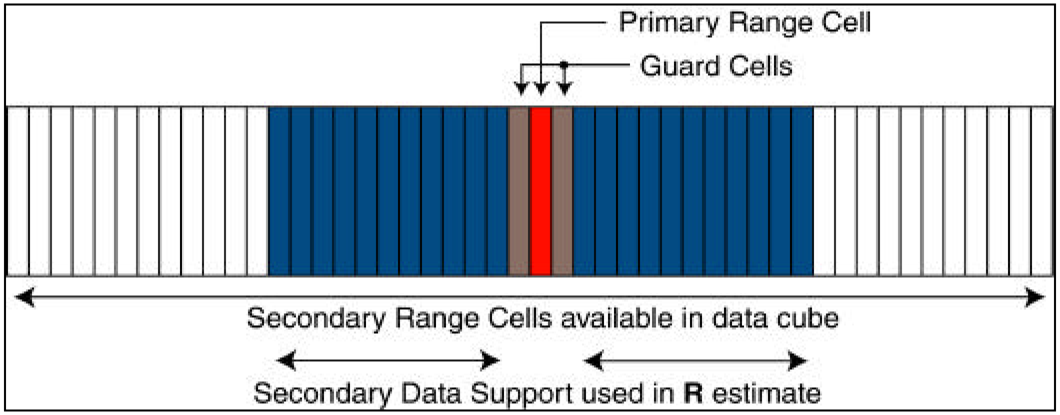
Accounting for MCARM array effects



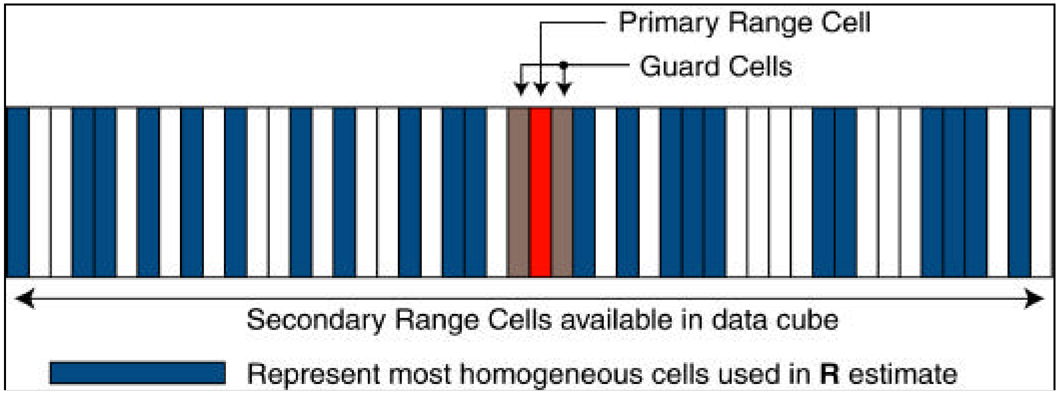
Processing Non-Homogeneous Data

- Statistical STAP Methods Estimate Covariance Matrix Using Secondary Data
  - Interference Assumed to be Homogeneous
- Real Radar Data is Non-Homogeneous
  - Terrain Variations
  - Multiple Interference Targets
  - Discretes/Blinking Jammers
- Use Non-Homogeneity Detector (NHD) or KB Map STAP
  - Eliminate Non-Homogeneous Cells From Estimate
  - Use JDL as our NHD

Secondary Data Selection



(a) Homogeneous Case

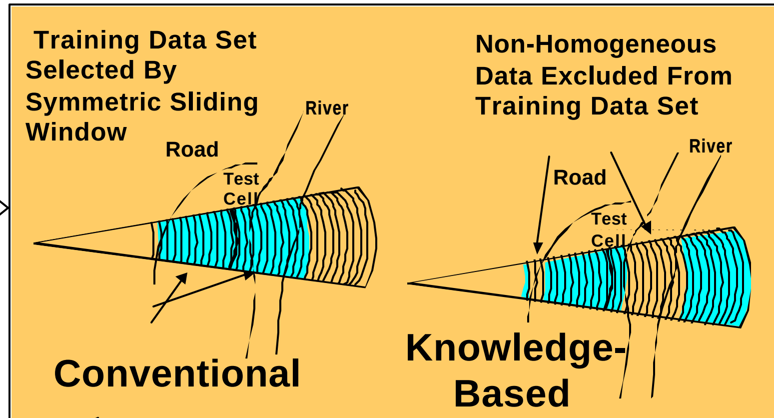


(b) Non-Homogeneous Case

Intelligent Sample Selection

KB Processing
NHD
LPR
JDL

Technique



Knowledge Sources

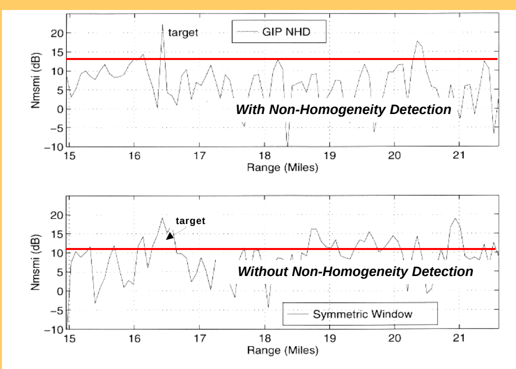
Measured Radar Data
Map Data
Other Sensors

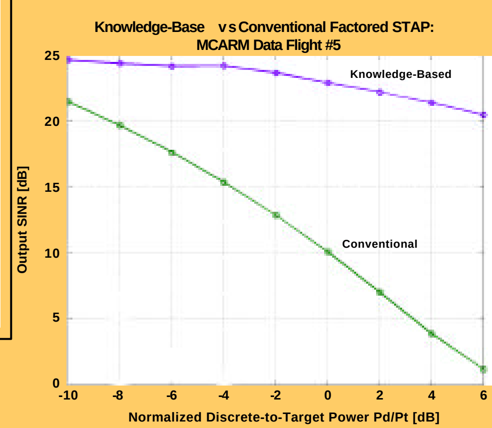
Filtering

Detection

Vector NHD

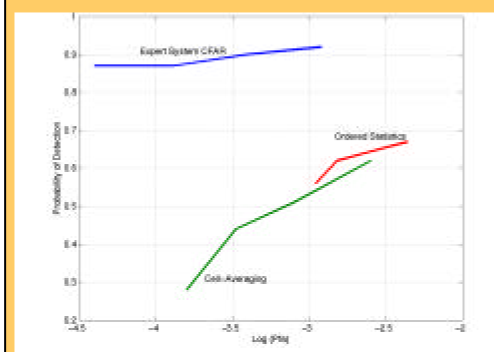
Measured MCARM Data Results





KBSTAP

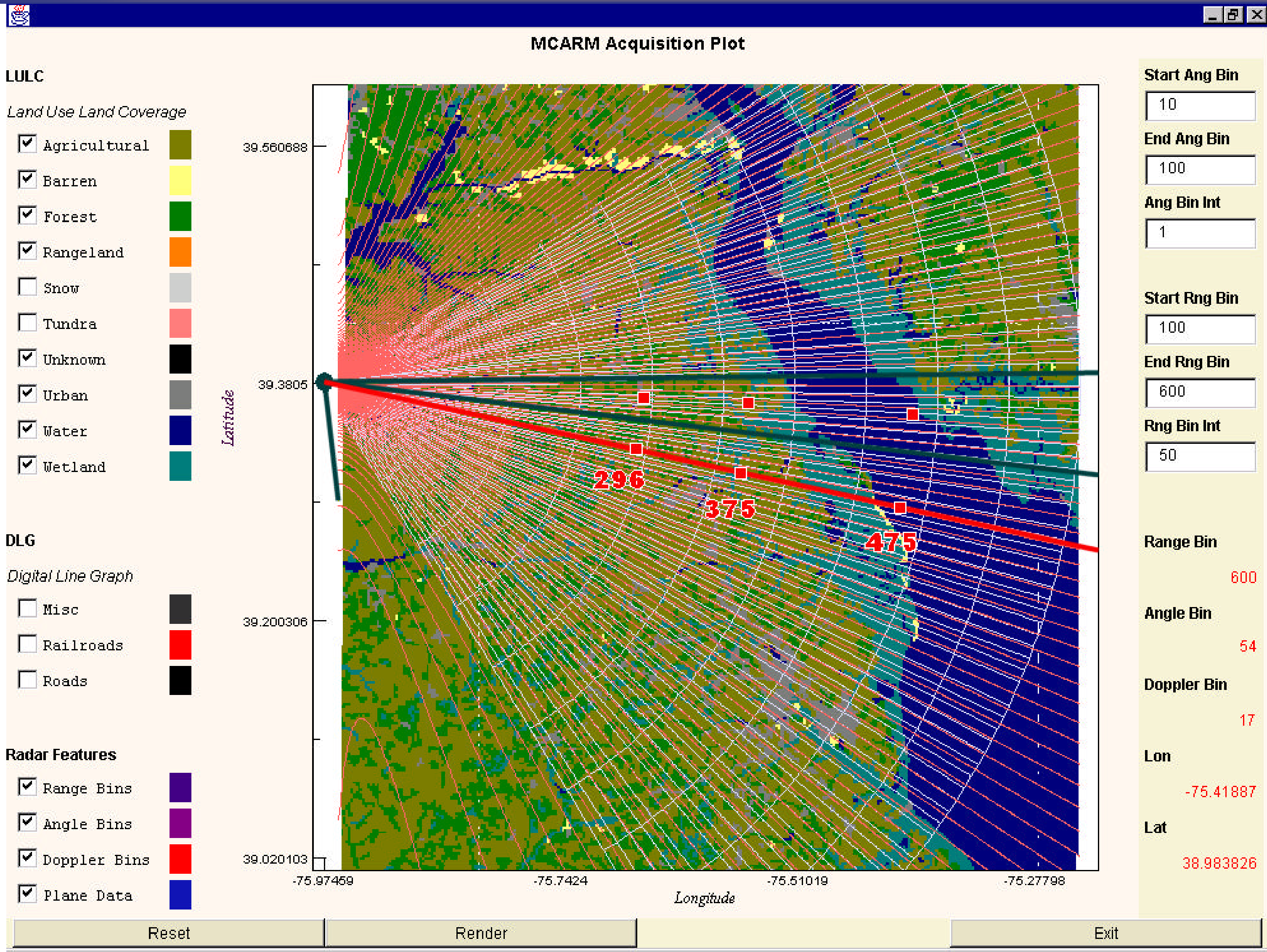
Measured E-3A Data Results



ES-CFAR

Scalar NHD

KB MAP STAP Training Data Selection



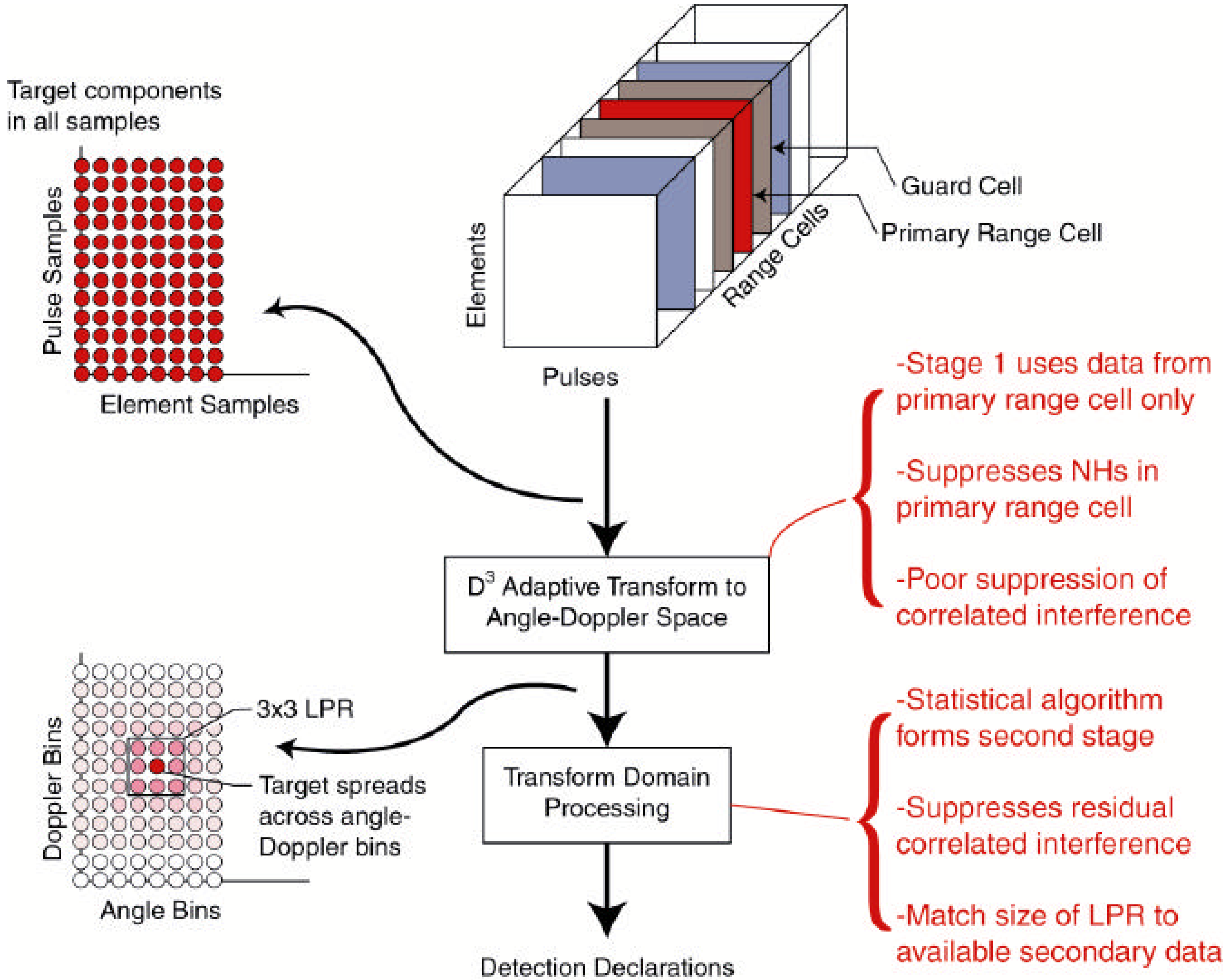
Radar Visualization of Terrain Clutter & Injected Targets

The Hybrid Method

Hybrid Methods – Why?

- **Motivation: How to Process Non-Homogeneous Cells?**
  - **Interference Has Correlated *And* Uncorrelated (Non-Homogeneous) Components**
- **Solution: Use a Hybrid Approach**
  - **Non-Statistical Processing Followed by Statistical Processing**

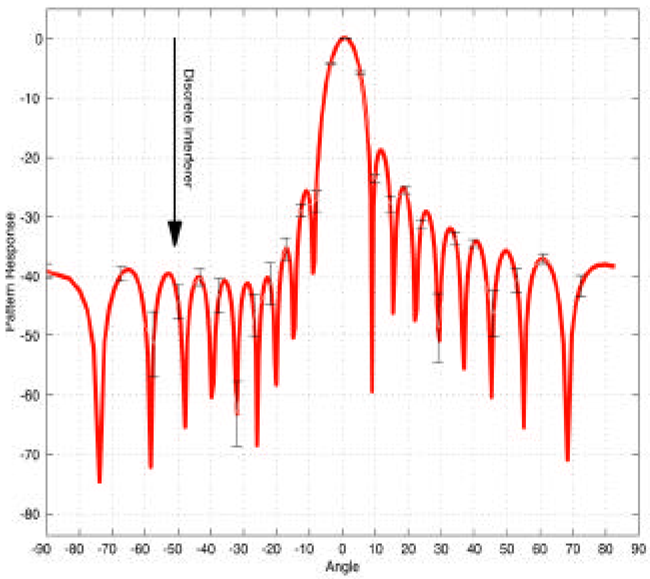
Block Diagram of the Two-Stage Hybrid Algorithm



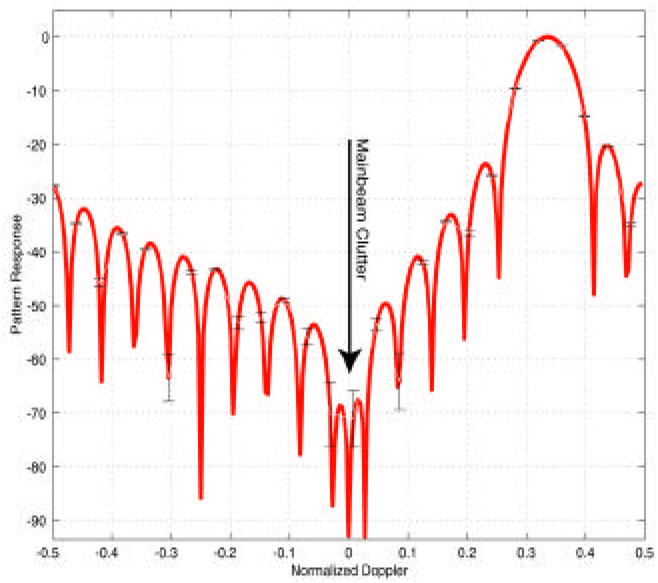
Performance Simulations

D3 (Direct Data Domain) Algorithm

Angle Response



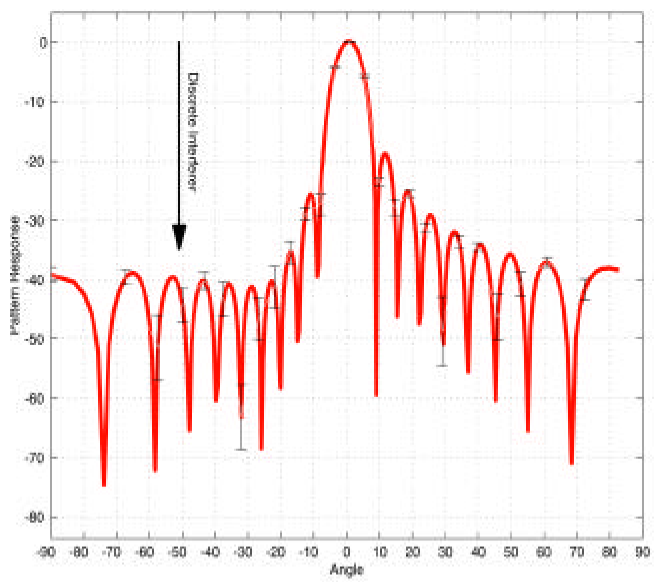
Doppler Response



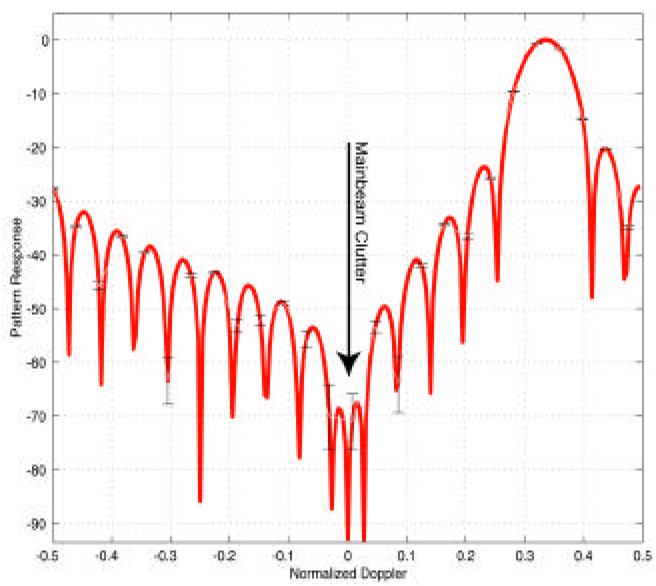
Performance Simulations

JDL Algorithm

Angle Response



Doppler Response

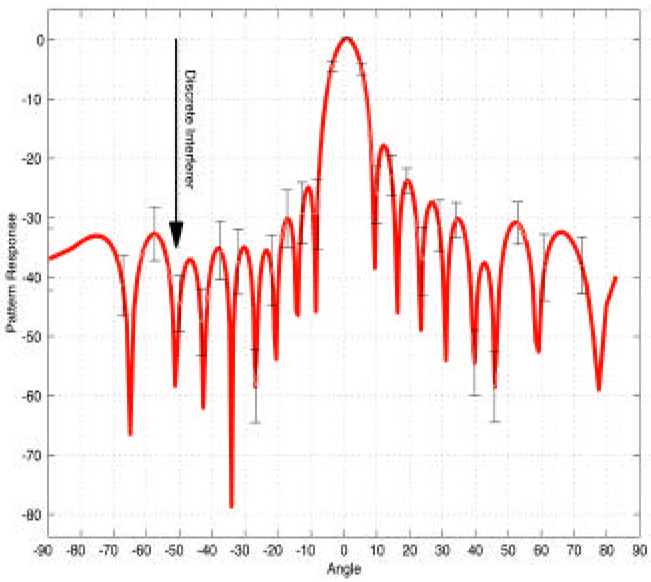


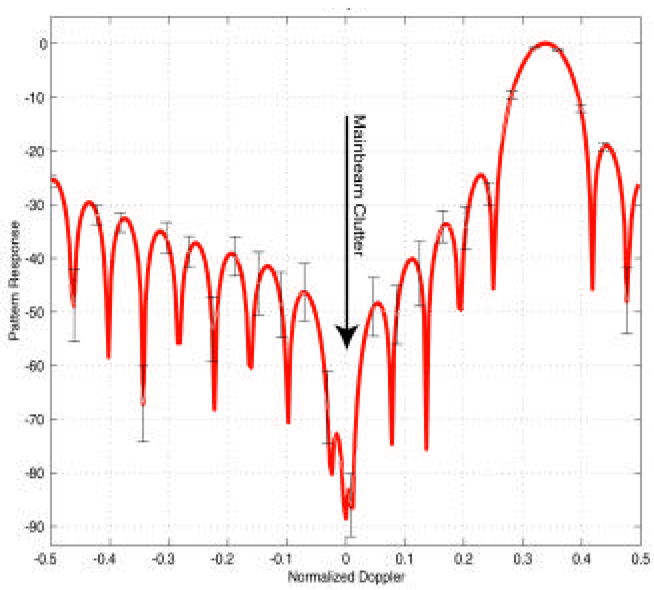
Performance Simulations

The Two-Stage Hybrid Method

Angle Response

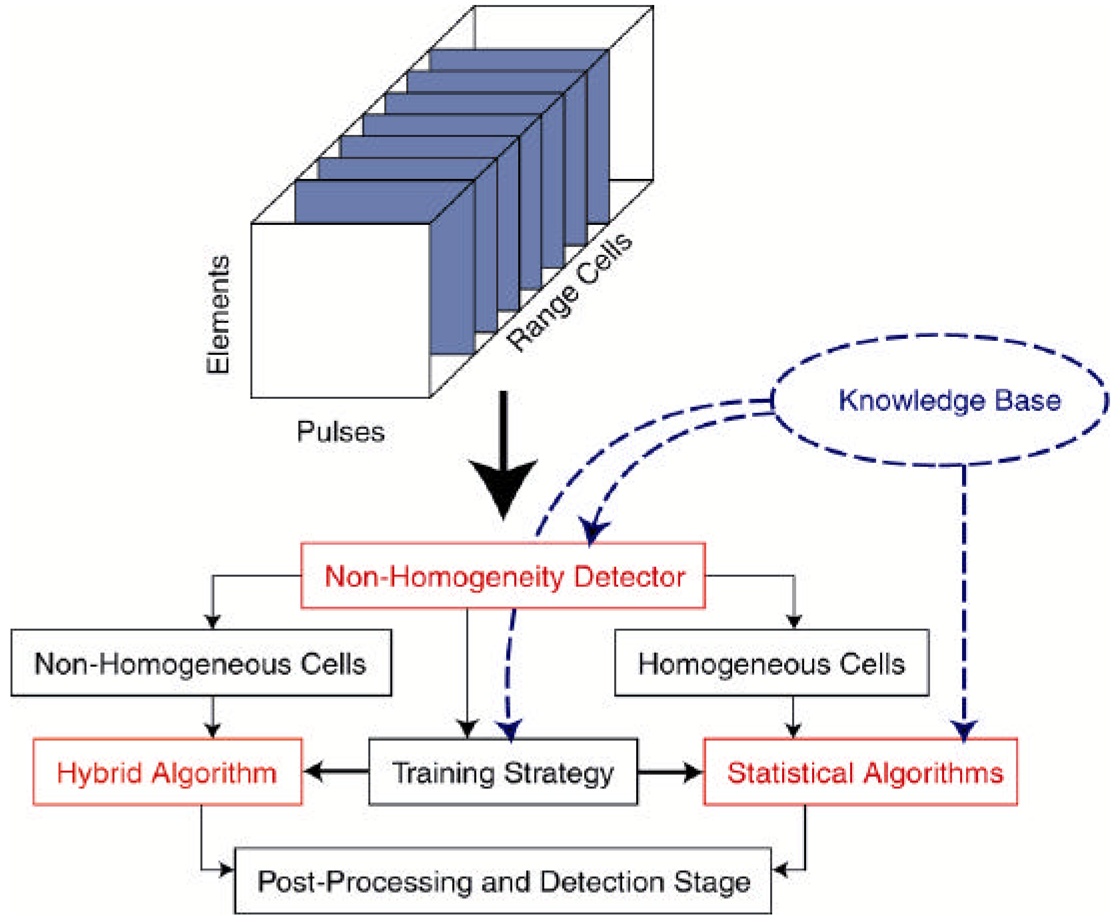
Doppler Response



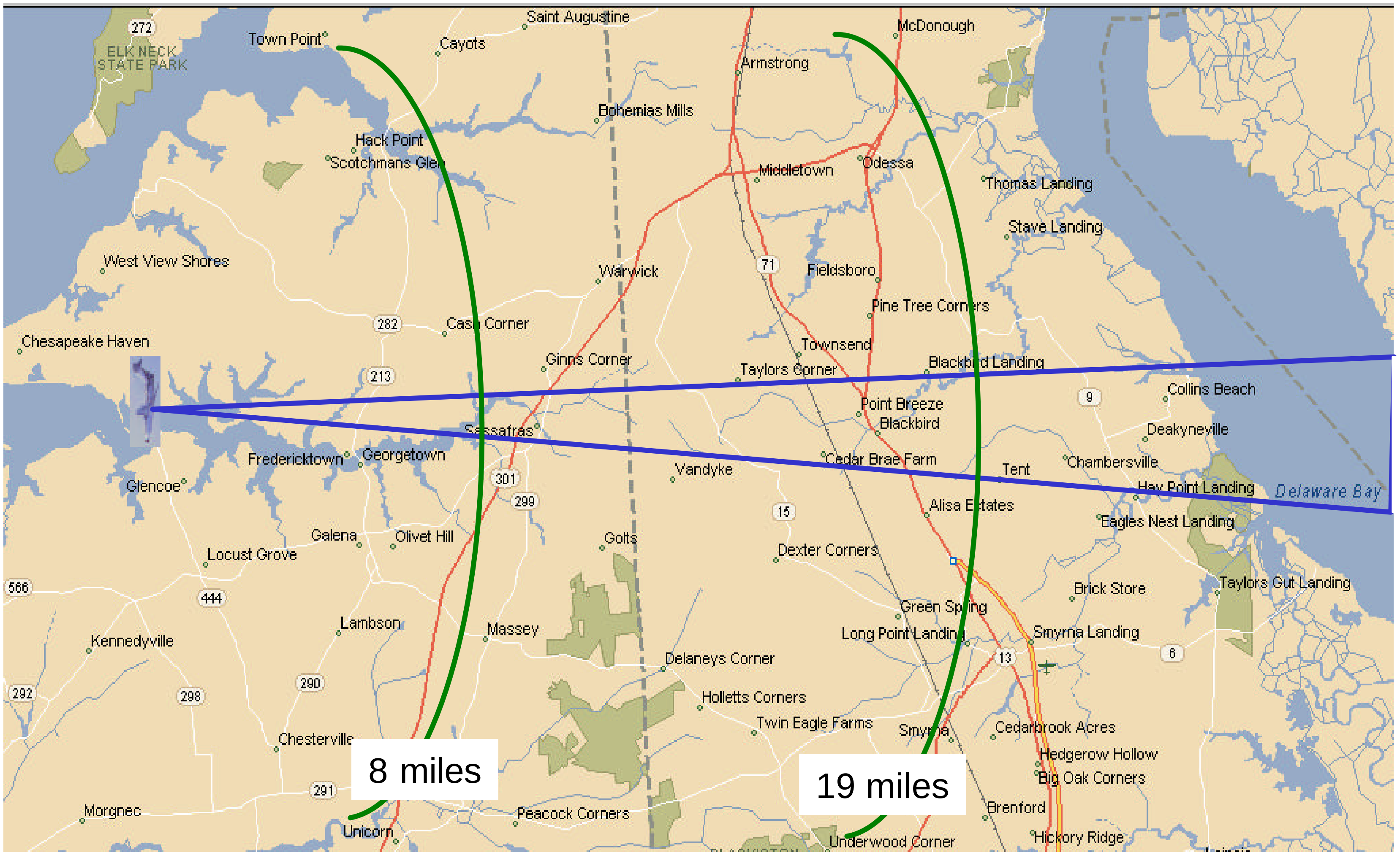


MCARM Data Analysis Using the Hybrid Method

Knowledge Based Space-Time Adaptive Processing (KB-STAP)



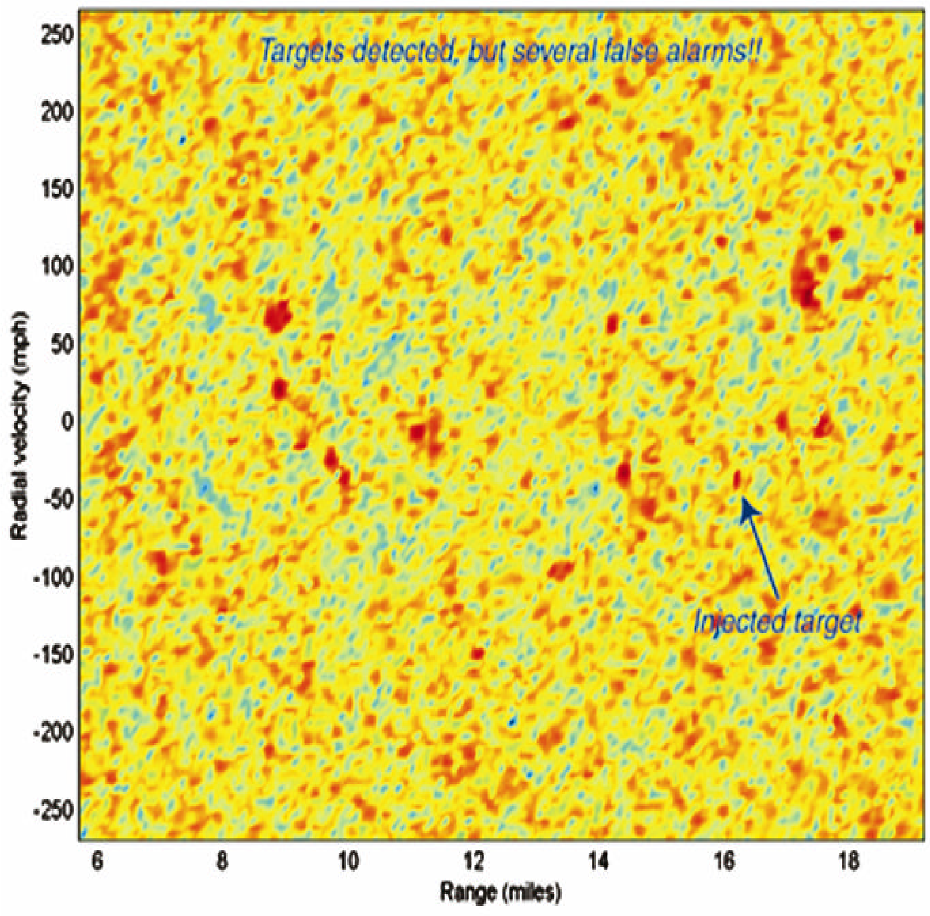
Data Source



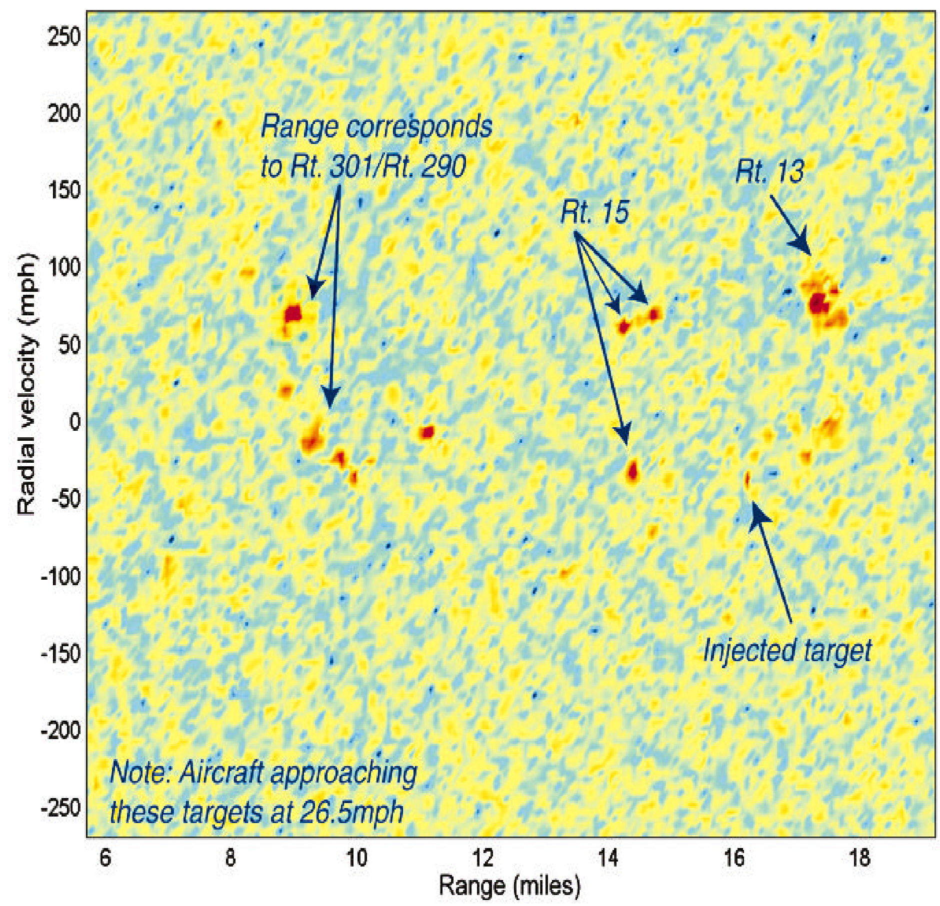
8 miles
19 miles
Delaware Bay
Town Point
Saint Augustine
Cayots
McDonough
Armstrong
ELK NECK STATE PARK
Bohemias Mills
Hack Point
Scotchmans Glen
Middletown
Odessa
Thomas Landing
Stave Landing
West View Shores
Warwick
Fieldsboro
Pine Tree Corners
Cash Corner
Chesapeake Haven
Ginns Corner
Townsend
Taylors Corner
Blackbird Landing
Collins Beach
Point Breeze
Blackbird
Sassafras
Deakyneville
Fredericktown
Georgetown
Cedar Brae Farm
Vandyke
Tent
Chambersville
Glencoe
Hay Point Landing
Alisa Estates
Eagles Nest Landing
Galena
Olivet Hill
Golts
Locust Grove
Dexter Corners
Brick Store
Taylors Gut Landing
Green Spring
Lambson
Massey
Long Point Landing
Smyrna Landing
Kennedyville
Delaneys Corner
Holletts Corners
Twin Eagle Farms
Smyrna
Cedarbrook Acres
Chesterville
Hedgerow Hollow
Big Oak Corners
Morgnec
Peacock Corners
Brenford
Unicorn
Underwood Corner
Hickory Ridge

Ground & Air Moving Target Indication

Classical STAP

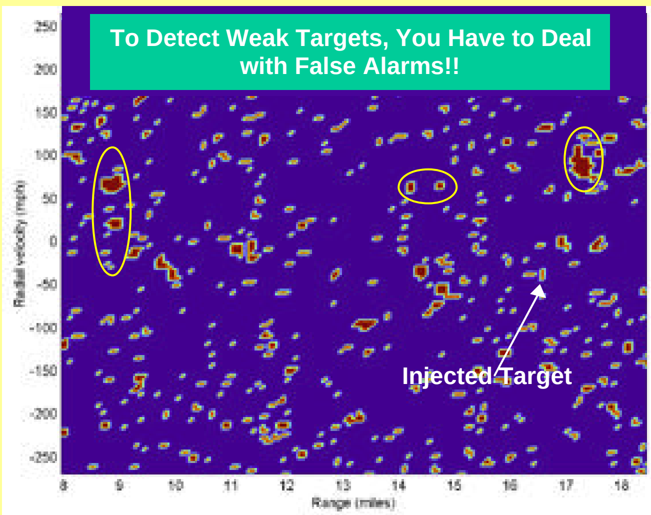


Combined Approach

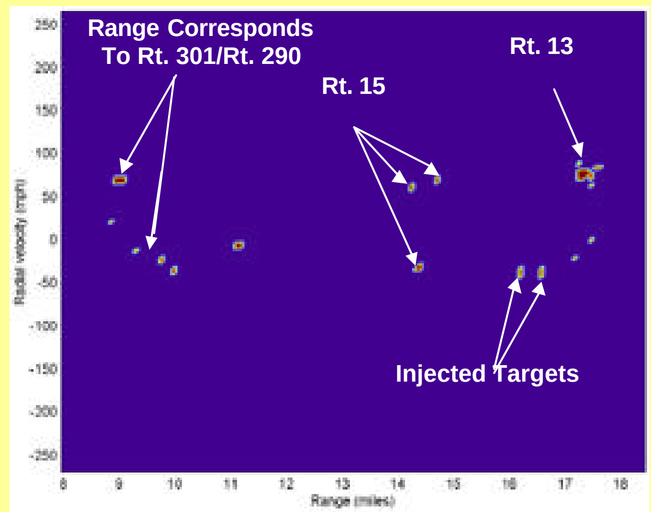


Enhanced Moving Target Indication Via KB-STAP

Classical STAP



STAP with Non-Homogeneity Detection



↴ KB-STAP Provides the Ability to See Ground Moving Targets Without Excessive False Alarms

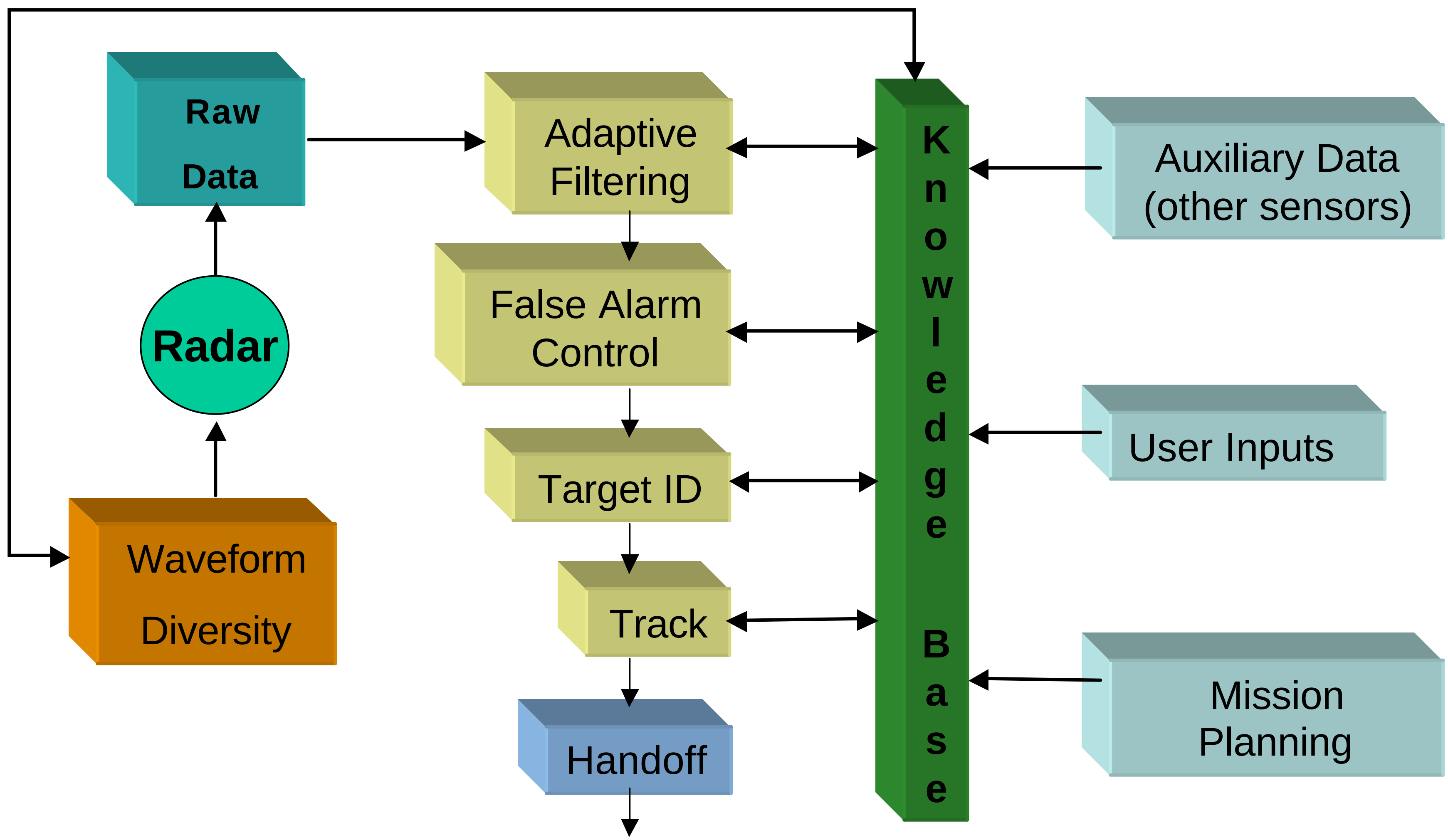
Observation

- We Must Use All Available Information
- We Must Account for Real World Effects
  - Essential to Move Adaptive Processing form Theory to Practice
    - Mutual Coupling
    - Non-Homogeneous Data
- Accounting for Real World Effects Will
  - Improve STAP Performance
  - Marginally Increase Computational Load

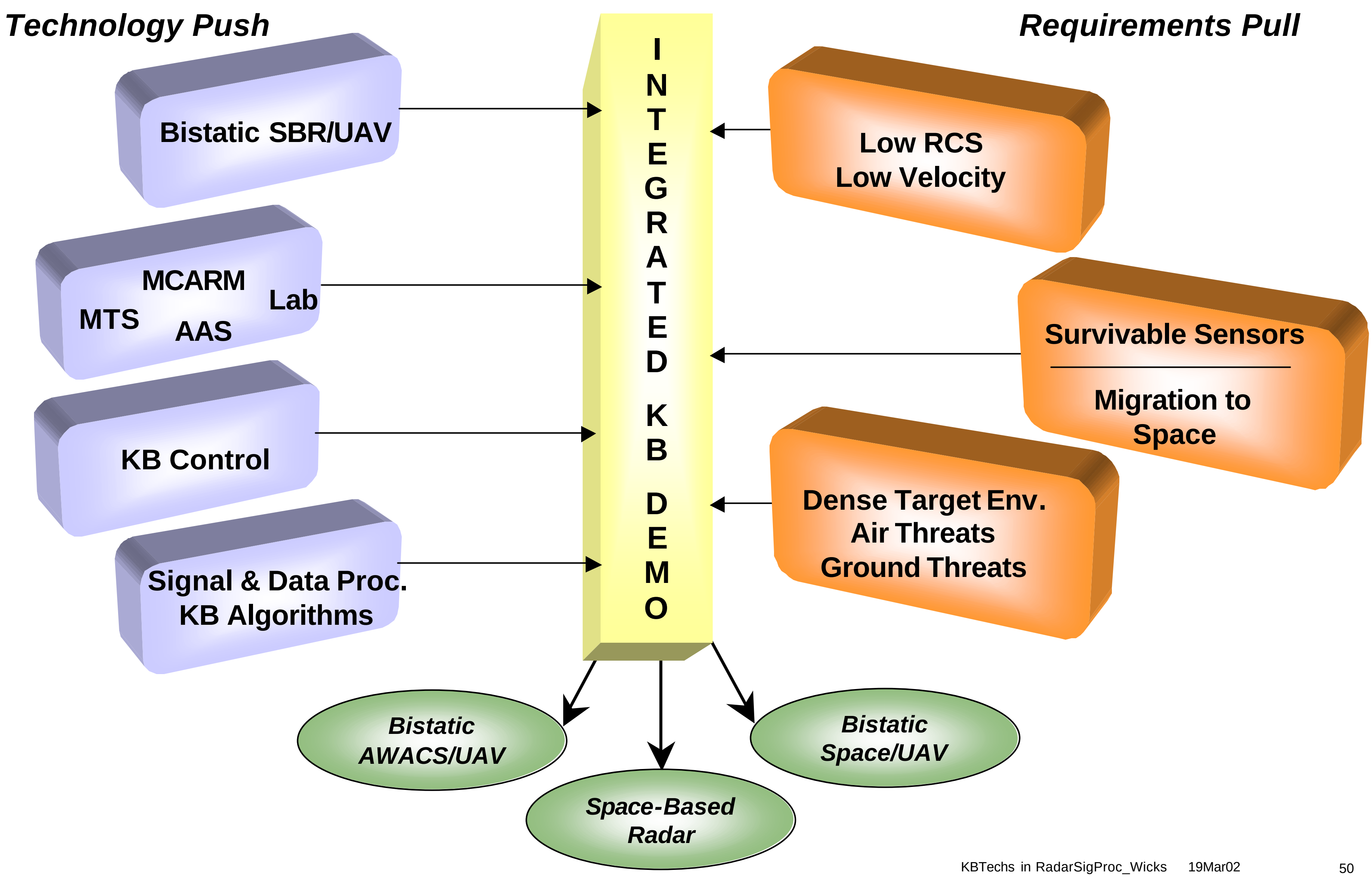
The Future

- Leverage Considerable Previous Investments
- Put Knowledge-Based Algorithms Into Fielded & Developmental Systems

Integrated End-to-End Radar Signal & Data Processing



Transition to Users



Conclusions

- **Maximum Leverage of Previous Investments**
- **Knowledge-Based Algorithms for Significant Performance Improvements**
  - **Multi-Pass Processing**
  - **End-to-End Integration**
  - **Knowledge-Based Control**
- **Real-Time Airborne Demonstration**
- **Transition to Fielded Systems**